Present-day Antarctic Ice Mass Changes and Crustal Motion

Thomas S. James' and Erik R. Ivins[2]

'Geophysics Division, Geological Survey of Canada

[2]Jet Propulsion Laboratory, California Institute of Technology

Abstract. The peak vertical velocities predicted by three realistic scenarios of Antarctic ice sheet mass balance are found to be of the order of several mm/a. One scenario predicts local uplift rates slightly in excess of 5 mm/a, These rates are small compared to the peak Antarctic vertical velocities of the ICE-3G glacial rebound model, which are in excess of 20 mm/a. If the Holocene Antarctic deglaciation history portrayed in ICE-3G is realistic, and if regional upper mantle viscosity is not an order of magnitude below 102] Pa ·s, then a vast geographical area in west Antarctica is uplifting at a rate that could easily be detected by a future Global Positioning System (GPS) campaign. While present-day scenarios predict small vertical crustal velocities, their overall continent-ocean mass exchange is large enough to account for a substantial portion of the observed secular polar motion ($\Omega\vec{m}$) and time-vatying zonal gravity field J_1.

Introduction

Changes in sea-level arc believed to occur chiefly in response to changes in the mass of the polar icc caps and mountain glaciers [e.g. *Warrick and Oerlemans*, 1991]. Understanding ice-mass changes is societally important because of the potential for inundation of coastal regions if sea-level should rise in the future. Ice-mass changes are known to significantly affect global geodetic observable such as the secular drift of the Earth's spin axis through the crust (polar motion) and the time-varying long-wavelength gravitational field [e.g. *Lambeck, 1980; Chao et al., 1987; Trupin, 1993; Mitrovica and Peltier, 1993]*, which suggests that observations of these quantities can provide indirect information on the sea-level budget.

Hager [199 1] proposed that the crustal motion resulting from ice-sheet mass changes could be significant, raising the possibility that ground geodetic observations could provide further information on ice-sheet mass balances. Observation of such motion would be extremely useful because secular polar motion and J_2 cannot provide a sufficient constraint on polar ice ablation/accumulation because other candidate sources exist for these quantities [*Lambeck and Cazenave, 1976; Chao et al., 1987].* In this paper we present vertical crustal motion rates, polar drift $\Omega\dot{\vec{m}}$, and the time varying zonal gravity harmonics $\dot{J}_{2-4}$ associated with contrasting, yet glaciologically realistic, scenarios for the net mass balance of the Antarctic ice-sheet, A residual isostatic motion related to the viscous memory of the mantle to Holocene glacial retreat is also considered.

Antarctic Ice-sheet Scenarios

Bentley and Giovinetto [1991] (henceforth BG91) evaluated measurements of accumulation and ablation from 12 Antarctic drainage basins and extrapolated to unmeasured regions in a number of ways. The unmeasured regions comprise approximately 30% of Antarctica by area; they tend to be located in coastal regions where accumulation rates are highest. Scenario 1 (Figure 1a), having a minimum ocean-continent hydrological exchange M, assumes that unmeasured regions are in equilibrium, Only measured regions with significant net mass imbalances were retained. The corresponding sca-level change is small: $\dot{\xi} = -0.1$ mm/a

(M = 36 Gt/a ice-sheet growth, see Table 1).

BG91 extrapolated from measured areas to unmeasured regions by assuming that the measured regions are characteristic of the ice-sheet as a whole. They extrapolated by mass accumulation (Figure lb), which yields the largest sea-level change $\dot{\xi}$ of -1.1 mm/a (Scenario 2; M = *400* Gt/a). For gridding purposes all the extrapolated mass was concentrated on coastal disks where accumulation rates are highest. A possible drawback of the BG91 scenarios is the prediction of sea-level fall (negative $\dot{\xi}$). This requires the Greenland ice sheet and/or mountain glaciers to be receding at rates much larger than what 20th century observations seem to indicate [*Warrick and Oerlemans*, *1991]*.

In contast, *Jacobs et al. [1992]* (J92) derived a net mass balance for Antarctica that employed data for the same 12 drainage basins but with substantially larger rate estimates of calving and melting at the ice sheet margins. Their study found a negative mass balance of the entire Antarctic ice sheet (both grounded and floating portions) of -469 Gt/a. In this study we have assumed that 35% of the negative mass balance comes from grounded portions, sufficient to cause 0,45 mm/a of sea-level rise (M = *-145* Gt/a). This amount of sea-level rise ($\dot{\xi}$ = 0.45 mm/a) is sufficient to explain the discrepancy between the Intergovernmental Panel on Climate Change's (IPCC) best estimate of present-day sea-level rise of 1.5 mm/a [*Warrick and Oerlemans*, 1991] and the sum (1.05 mm/a) of their best estimates of the individual contributions to sea-level rise from ocean thermal expansion (0.4 mm/a), mountain glaciers (0.4 mm/a), Greenland (0.25 mm/a), and Antarctica (0.0 mm/a). The J92 scenario is more realistic if mass wastage estimates are, in fact, improvements over the BG91 estimates. Particularly important arc basal melt-rates which are now thought (o bc greater than -500 Gt/a [*Jacobs*, 1992]. The J92 Scenario was produced by revising a BG9 1 extrapolation to reflect retreat of ice-shelf grounding lines (Figure 1 c). Grounding line retreat was assumed to occur principal] y on the Filchner-Ronne ice-shelf.

Results

Plate 1 shows the predicted vertical velocities for the 3 scenarios. Peak velocities are typically located in the centre of drainage basins and have magnitudes of 3-4 mm/a. The largest vertical velocities (-8 mm/a) were obtained from the J92 Scenario where the grounding line of the Filchner-Ronne ice shelf (Figure 2) is assumed to be retreating. The largest velocities are not produced from the scenario causing the largest sea-level change, but rather from a scenario in which there is substantial internal ice-mass shifting, that is, growth in one region offset by depletion in another.

In gridding the scenarios we generally assumed a uniform change in each drainage basin or region. Exceptions to this were the extrapolation solely to coastal regions for Scenario 2, and ablation of the Filchner-Ronne ice-shelf in the J92 Scenario. The assumption of uniform change has the effect of dispersing a given mass imbalance over a region, rather than concentrating the mass imbalance, which would cause larger velocities. To the extent that on-going ice-mass changes in Antarctica will induce detectable uplift rates, it is likely that internal, but probably not continent-wide, imbalances are most significant, The vertical velocities resulting from a scenario considered by *Trupin [1993]* support this. *Trupin [1993]* subtracted a uniform mass layer of sufficient magnitude to yield a zero net sea-level change from Antarctic accumulation rates. This scenario, which has substantial internal mass shifting, but no net mass change, yields vertical velocities ranging from larger than 5 mm/a to less than -10 mm/a, a substantially greater range of velocities than those resulting from the glaciological scenarios considered here.

Over much of Antarctica, the vertical signal from glacial rebound may dominate that caused by present-day ice-mass changes. Plate 1 d shows the predicted vertical velocities in Antarctica due to the ICE-3G glacial rebound model of *Tushingham and Peltier [1991]*, which was used to load a seismically-realistic Earth model having a Maxwell rheology and a lower-mantle viscosity of 2 x 1021 Pa·s, upper-mantle viscosity of 10^{21} Pa-s, and lithospheric thickness of 120 km. Peak velocities are larger than 20 mm/a, more than twice the peak velocity of the J92 Scenario. It is noteworthy that if the J92 velocities are combined with the ICE-3G velocities, then velocities over large portions of West Antarctica are predicted to be in excess of 20 mm/yr. Sites in the trans-Antarctic Mountains and the Ellsworth Mountains (Figure 2) would give substantial vertical signals which could be detected in future GPS campaigns.

Although the ice-mass change scenarios considered here produce marginally detectable vertical velocities, the predicted secular changes in polar motion and the long-wavelength gravitational field are substantial. Table 1 shows the predicted secular change of polar motion and the degree 2, 3, and 4 zonal gravity harmonics (J_l) produced by the 3 scenarios. Also given in Table 1 are secular zonal rates recently deduced from the nodal drift of the Ajisai, Starlette, and Lageos- 1 geodynamics satellites [*Nerem and Klosko*, 1994]. The observed secular change of J_2 is -21 (± 3) x 10^{12} /a, comparable in magnitude, although of opposite sign, to the value predicted for J92. The predicted magnitude of the secular drift of the pole ranges from 15% to 4070 of the observed secular drift of 3.0 ± 1 mas/a [*Lambeck*, 1980], Present-day ice mass changes must be considered in constructing budgets for these global geodetic observables.

In summary, the three present-day ice-mass change scenarios considered here predict peak vertical velocities less than 10 mm/a, and with 1 exception, less than 5 mm/a. Perhaps larger vertical velocities are induced by localized mass transfer (e.g., rapidly changing ice streams) or by long-term mass wasting which draws part of its response from mantle dislocation processes. Regarding either of these possibilities, the lack of geomorphological and glaciologically-based data restricts elaborate uplift modelling. The velocities presented here represent minimum, or conservative, estimates of the crustal motion due to present-day ice-mass changes. These values are small compared to the peak velocities (-20 mm/a) predicted by the ICE-3G glacial rebound model [*Tushingham and Peltier*, 1991], indicating the importance of a Holocene 'memory' component of crustal motion in Antarctica, In contrast, ice-mass change scenarios predict secular rates for polar motion and the low-degree zonal harmonics that are quite substantial, in agreement with earlier studies [e.g. *Lambeck*, 1980; *Chao et al.*, 1987; *Sabadini et al.*, 1988; *Trupin*, 1993; *Mitrovica and Peltier*, 1993].

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References

Bentley, C. R., and M. B. Giovinetto, Mass balance of Antarctica and sea level change, in *Polar Regions and Climate Change, Proc. Symp. Univ. Alaska, Fairbanks, June* 1990, ed. G. Weller, C. L. Wilson, and B. A. B. Severin, 481-488, 1991.

Chao, B. F., W. P. O'Connor, A. T. C. Chang, D. K. Hall and J. L, Foster, Snow load effect on the earth's rotation and gravitational field, 1979-1985, *J. Geophys Res.*, 92, 9415-9422, 1987.

Hager, 13. H., Weighing the ice sheets using space geodesy: A way to measure changes in ice sheet mass, *EOS Trans. AGU, 17*, p. 91, 1991.

Jacobs, S. S., Is the Antarctic ice sheet growing?, *Nature*, 360, 29-33, 1992.

Jacobs, S. S., H. H. Helmer, C. S. M. Doake, A. Jenkins, and R. M. Frolich, Melting of ice shelves and the mass balance of Antarctica, *J. Glaciology*, 38, 375-387, 1992.

Lambeck, K., *The Earth's Variable Rotation*, Cambridge Univ. Press, Cambridge, 449 pp., 1980.

Lambeck, K., and A. Cazenave, Long term variations in the length of the day and climatic change, *Geophys. J. Roy. astr. Sot., 46, 555-573, 1976.*

Mitrovica, J. X., and W. R. Peltier, Present-day secular variations in the zonal harmonics of Earth's geopotential, *J. Geophys. Res.*, 98, 4509-4526, 1993.

Nerem, R. S., and S. M. Klosko, Secular variations of the Earth's gravitational field determined from Satellite Laser Ranging, *Geophys. Res. Lett.*, in prep., 1994.

Sabadini, R., D. A. Yuen, and P. Gasparini, Mantle rheology and satellite signatures from present-day glacial forcings, *J. Geophys. Res.*, 93, 437-447, 1988.

Trupin, A. S., Effect of polar ice on the Earth's rotation and gravitational potential, *Geophys. J.*

Int., *113, 273-283, 1993.*

Tushingham, A. M. and W. R. Peltier, ICE-3G: A new global model of late Pleistocene deglaciation based upon geophysical predictions of post-glacial relative sea-level change, *J. Geophys. Res.*, 96, 4497-4523, 1991.

Warrick, R. A., and H. Oerlemans, Sea Level Rise, in *Climate Change The IPCC Scientific Assessment*, ed. J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, Cambridge Univ. Press, Cambridge, 1991.

Figure Captions

Figure 1. Secular mass changes (in mm/a of ice equivalent) for 280 equally sized disks. The height change assigned to each disk corresponds to the 3 glaciologically -based scenarios: (a) Scenario 1; (b) Scenario 2; (c) J92 Scenario.

Figure 2. Location map,

Plate 1. Vertical velocities for the three present-day ice-mass change scenarios and duc to the ICE-3G Holocene ice sheet reconstruction of *Tushingham and Peltier* [1991]. Displacement rates for the present-day scenarios duc to the growth or ablation of all disks (Figure 1) were determined using elastic Love numbers summed to spherical harmonic degree 240. Computations were checked against a Green's function formulation.

Table . Sea- evel Change $\dot{\xi}$, Ice-mass Change $\dot{M}$, and Secular Changes in Zonal Harmonics J_l and Polar Motion $\Omega\vec{m}$

Quantity	Scenario			Observed
	1	2	J92	
$\dot{\xi}$ (mm/a)	-0.1	-1.1	0.45	1.05†
$\dot{M}$ (Gt/a)	36	400	-145	
$\dot{J}_2$ (10^{-12} /a)	-5	-41	18	-21
$\dot{J}_3$ (10^{-12} /a)	5	40	-19	23
$\dot{J}_4$ (10^{-12} /a)	-5	-34	19	-48
$\Omega\vec{m}$	154°W	120°E	128°E	71°W
$\lvert\Omega\vec{m}\rvert$ (mas/a)	0.47	0.56	1.13	3

†sum of IPCC best estimates [*Warrick and Oerlemans*, 1991]

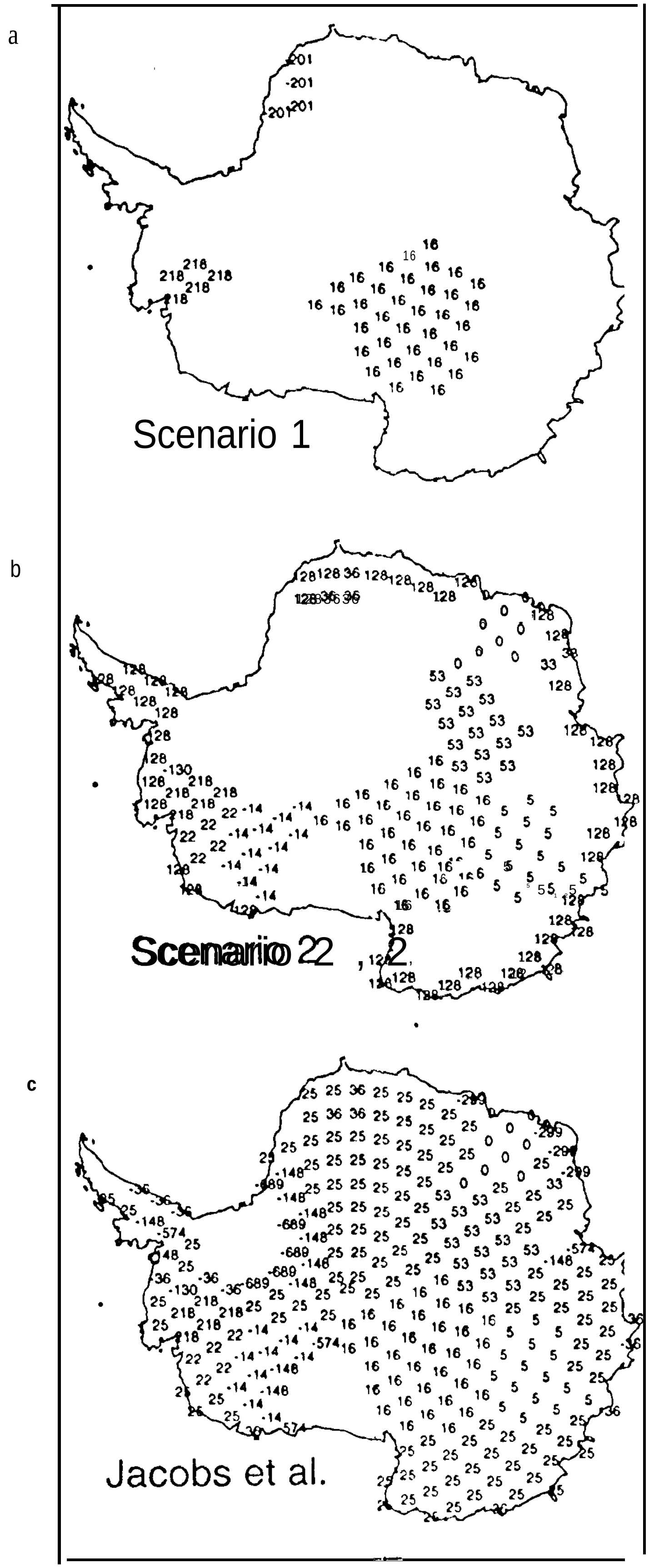


Fig. 1

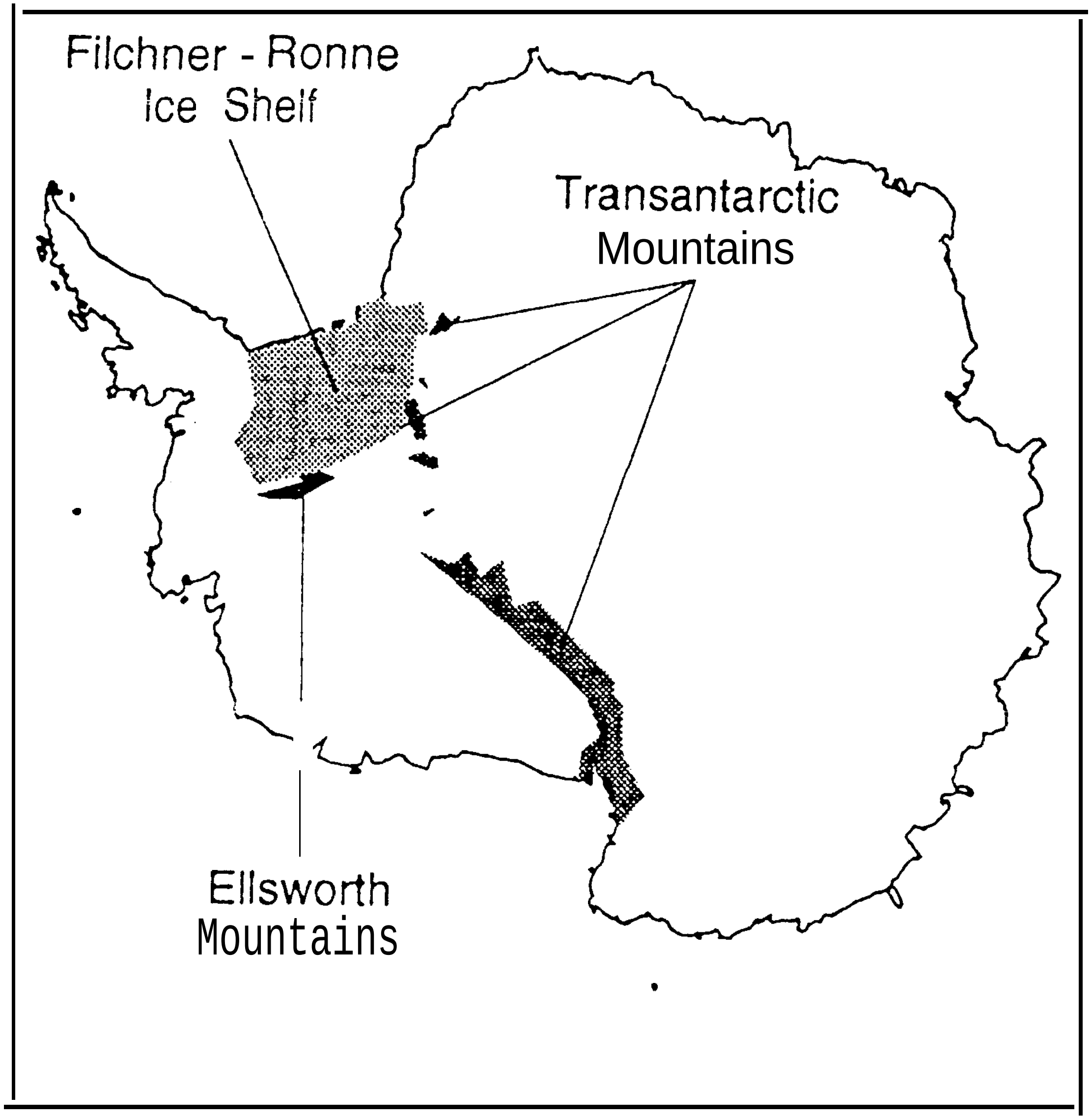
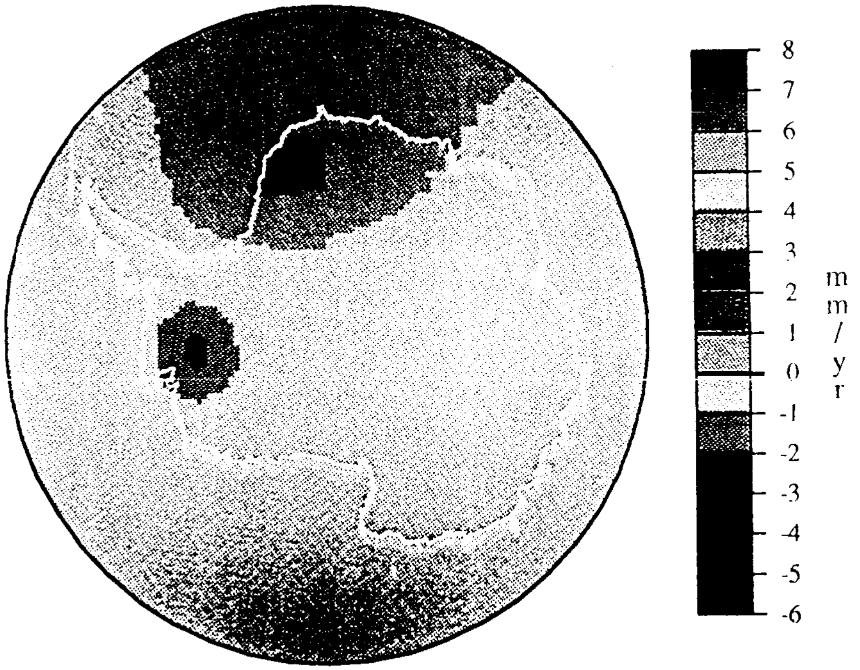

Filchner - Ronne
Ice Shelf
Transantarctic
Mountains
Ellsworth
Mountains

Fig. 2

Scenari⊖1; Vertical Velocity



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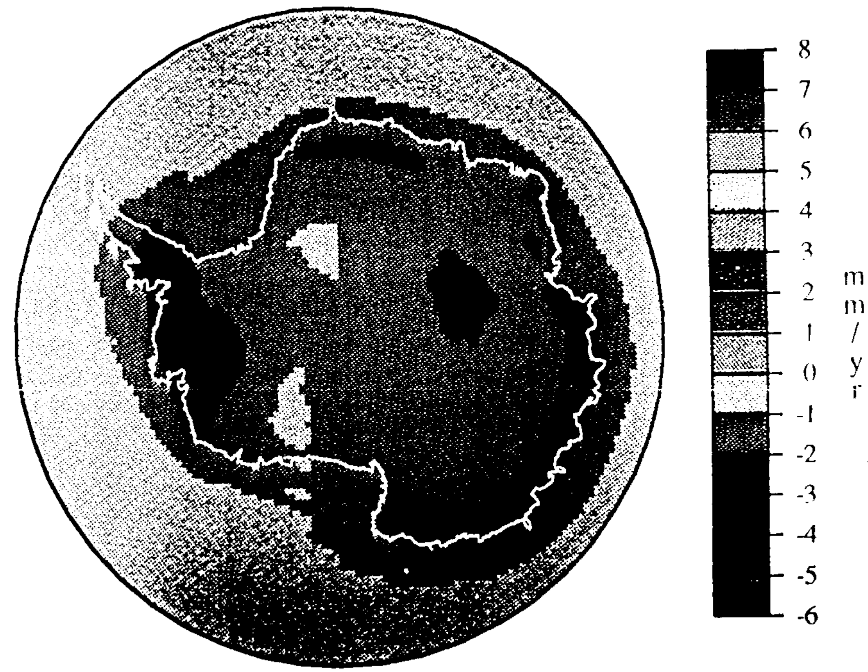
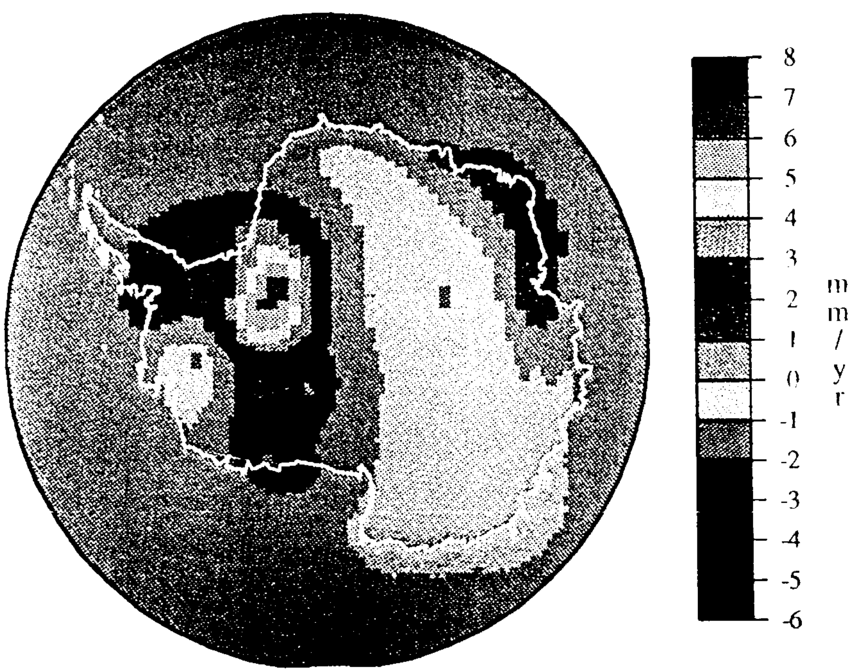


Jacobs et al.; Vertical Velocity



ICE-3G